# Navy Northwest Training and Testing Phase II

# Sonar and Explosive Criteria for Fishes

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## Introduction

This document is being prepared to support the Navy's Northwest Training and Testing (NWTT) Phase II EIS/OEIS and associated regulatory consultations.

Sound exposure criteria proposed for fishes is provided in Table 1 below. These criteria were largely derived from the extensive review provided in Popper et al. (2014) "Sound Exposure Guidelines for Fishes and Sea Turtles". Thresholds within that technical report are generally presented at the lowest level at which the effect occurred. In some cases the thresholds presented in Popper et al. (2014) did not show any effect but are the only data available for that stressor. These guidelines therefore may be overly conservative. Exposure guidelines for Navy explosives rely on an equation from Young (1991), modified using Yelverton et al. (1975), to predict ranges to effect for 'No Injury' (i.e., onset of injury would be expected at some higher exposure) and for 1% Mortality. A description of each cell is presented below to explain the derivation of the threshold value proposed.

Thresholds for TTS are typically reported in cumulative sound exposure level ($SEL_{cum}$) so as to account for the duration of the exposure and therefore are presented in terms of $SEL_{cum}$ metric within this document.

**Acoustic Units use in this Document**

$SEL_{cum}$ - Cumulative sound exposure level (dB re 1 μPa$^2$·s)

$SPL_{rms}$ - Root mean square sound pressure level (dB re 1 μPa)

$SPL_{peak}$ - Peak (0 – peak) sound pressure level (dB re 1 μPa)

**Acoustic Calculations used in this document (see Richardson 1995)**

$SEL_{cum} = SPL_{rms} + 10 \log t$

Where t = duration of exposure in seconds

**Table 1: Sound exposure criteria for fishes exposed to Navy sonar.**

| | **Low-Frequency Navy Sonar ( < 1 kHz)** | | | | | |
|---|---|---|---|---|---|---|
| | Row Letter | A | B | C | D | E |
| Col # | | **Mortality & mortal injury** | **Recoverable injury** | **TTS** | **Masking** | **Behavior** |
| 1 | Fish-no SB (swim bladder) | >> 218 dB $SEL_{cum}$ | > 218 dB $SEL_{cum}$ | > 218 dB $SEL_{cum}$ | (N) Low (I) Low (F) Low | (N) Low (I) Low (F) Low |
| 2 | Fish w/ SB not involved in hearing (particle motion detection) | >> 218 dB $SEL_{cum}$ | > 218 dB $SEL_{cum}$ | 210 dB $SEL_{cum}$ | (N) Low (I) Low (F) Low | (N) Low (I) Low (F) Low |
| 3 | Fish w/ SB used in hearing (pressure detection) | >> 218 dB $SEL_{cum}$ | > 218 dB $SEL_{cum}$ | 210 dB $SEL_{cum}$ | (N) Mod (I) Low (F) Low | > 197 dB $SPL_{rms}$ |
| | **Mid-Frequency Navy Sonar (1-10 kHz)** | | | | | |
| | | **Mortality & mortal injury** | **Recoverable injury** | **TTS** | **Masking** | **Behavior** |
| 4 | Fish-no SB | >> 221 dB $SEL_{cum}$ | > 221 dB $SEL_{cum}$ | NA | NA | NA |
| 5 | Fish w/ SB not involved in hearing (particle motion detection) | >> 221 dB $SEL_{cum}$ | > 221 dB $SEL_{cum}$ | NA | NA | NA |
| 6 | Fish w/ SB used in hearing (pressure detection) | >> 221 dB $SEL_{cum}$ | > 221 dB $SEL_{cum}$ | 220 dB $SEL_{cum}$ | (N) Low (I) Low (F) Low | 200 dB $SPL_{rms}$ |
| | **Navy Explosives** | | | | | |
| | | **Mortality & mortal injury** | **1% Mortality and No Injury*** | **TTS** | **Masking** | **Behavior** |
| 7 | Fish-no SB | 229 dB $SPL_{peak}$ | ---- | >>186 dB $SEL_{cum}$ | NA | (N) High (I) Mod (F) Low |
| 8 | Fish w/ SB not involved in hearing (particle motion detection) | 229 dB $SPL_{peak}$ | Range equation | >186 dB $SEL_{cum}$ | NA | (N) High (I) High (F) Low |
| 9 | Fish w/ SB used in hearing (pressure detection) | 229 dB $SPL_{peak}$ | Range equation | 186 dB $SEL_{cum}$ | NA | (N) High (I) High (F) Low |

Diagonal stripe= not part of NWTT consultation
NA = No data available or threshold is not applicable to fish
(N) = near (i.e. tens of meters from the source)
(I) = intermediate (i.e. 100s of meters from the source)
(F) = far (thousands of meters form the source)
High, Mod (moderate), and Low = Probability of the effect occurring. For any cell containing these designations please see Popper et al. (2014) for meaning.
* 1% Mortality and No Injury = Survivability Curve equation is presented in Young (1991) and adjusted using data from Yelverton et al. (1975). 'No injury' relates to data in which no injuries were observed; onset of injury (i.e., $LD_1$) would be at some higher exposure.

Background

This section should review physiology and set up swim bladder w hearing adaptations vs not. And dismiss most non swim bladder fish for any criteria consideration.

Low-Frequency Navy Sonar

- M*ortality, Mortal Injury, and Recoverable Injury: All Fish =* > 218 dB $SEL_{cum}$ *(cells A1, A2, A3, B1, B2 & B3)*
    - o Sonar has not been known to cause mortality, mortal injury, or recoverable injury in the wild due to lack of fast rise times, lack of high peak pressures, and lack of high acoustic impulse associated with some impulsive sounds (e.g., explosives). Long duration exposures (up to 2 hours) of sonar to fish in laboratory settings has caused stunning and mortality in some cases but these exposures were much longer than any exposure a fish would normally encounter in the wild due to NWTT proposed activities. In addition, the subjects exposed in the lab were held in a cage for the duration of the exposure, unable to avoid the source (Hastings 1991, Hastings 1995). Exposure to low-frequency sonar has been tested at levels up to 193 dB $SPL_{rms}$ for 324 seconds (218 dB $SEL_{cum}$) and has not been shown to cause mortality or any injury in fish with swim bladders (Popper et al. 2007, Kane et al. 2010). Lesser potential for injurious effects would be expected for fish without air cavities (i.e., swim bladders). Therefore the recommended threshold would be >> 218 dB $SEL_{cum}$ for mortality and > 218 dB $SEL_{cum}$ for recoverable injury.
- *TTS*: Fish-no SB = > 218 dB $SEL_{cum}$ *(cell C1)*
    - o Exposure to low-frequency sonar has not been shown to induce TTS in fish species without swim bladders (Popper et al. 2014).
- *TTS*: Fish w/ SB = 210 dB $SEL_{cum}$ *(cells C2 & C3)*
    - o Exposure to sonar above 1 kHz has been known to induce TTS in some fish species with swim bladders (Popper et al. 2007, Halvorsen et al. 2013). Subjects from Popper et al. (2007) may have undergone varying husbandry treatments or possessed different genetics which may have resulted in higher than normal shifts. Criteria provided in Popper et al. (2014) were reported in dB $SPL_{rms}$. This criteria was converted to SEL based on the signal durations reported in Popper et al. (2007) and Halvorsen et al. (2013) and was rounded down from the lowest sound exposure level as a conservative measure.

      193 dB SPLrms + 10log(324 sec) = 218 dB $SEL_{cum}$ (Popper et al. 2007)
- *Masking:* Fish w/out SB and Fish w/ SB not involved in hearing = (N)Low, (I)Low, (F)Low *(cells D1 &, D2)*
    - o No data are available on masking by sonar but it is unlikely that sonar would mask important sounds for fish. Risk of significant masking occurring within any distance from the source is low (Popper et al. 2014). The narrow bandwidth of most sonar would result in only a limited range of frequencies being masked (Popper et al. 2014). Furthermore most sonars are intermittent (i.e., low duty cycle) which further lowers the probability of any masking effects.
- *Masking:* Fish w/ SB involved in hearing = (N)Mod, (I)Low, (F)Low *(cell D3)*
    - o No data are available on masking by sonar but it is unlikely that sonar would mask important sounds for fish. The risk of masking occurring is moderate near the source and low at intermediate and far distances from the source (Popper et al. 2014); however, the narrow bandwidth of most sonar would result in only a limited range of frequencies being masked (Popper et al. 2014). Furthermore most sonars are intermittent (i.e., low duty cycle) which further lowers the probability of any masking effects.
- *Behavior:* Fish no SB and Fish w/ SB not involved in hearing = (N)Low, (I)Low, (F)Low *(cells E1 & E2)*
    - o No data are available on behavioral reactions to low-frequency sonar. Fish without a

mechanism to sense pressure are unlikely to sense sound beyond the near-field. The risk that sonar would result in a behavioral response within near, intermediate or far distances from sonar is low (Popper et al. 2014).

- *Behavior:* Fish w/ SB involved in hearing = > 197 dB $SPL_{rms}$ *(cell E3)*
  - No reactions were seen in fish exposed to 1-2 kHz sonar which is categorized as mid-frequency sonar, not low-frequency sonar. Therefore criteria used for behavioral reactions to sonar was taken from Popper et al. (2014), > 197 dB $SPL_{rms}$ (Doksaeter et al. 2009, Doksæter et al. 2012).

Mid-Frequency Navy Sonar

- M*ortality, Mortal Injury & Recoverable Injury:* >> 221 dB $SEL_{cum}$ *(cells A4, A5, A6, B4, B5, & B6)*
  - Sonar is not anticipated to cause mortality, mortal injury, or recoverable injury due to lack of fast rise times, lack of high peak pressures, and lack of high acoustic impulse associated with some impulsive sounds (e.g., explosives). Exposure to mid-frequency sonar has been tested and has not been shown to cause mortality or any injury in fish with swim bladders (Popper et al. 2007, Kane et al. 2010). Lesser potential for injurious effects would be expected for fish without air cavities (i.e., swim bladders). Therefore the recommended threshold would be >> 221 dB $SEL_{cum}$ for mortality and > 221 dB $SEL_{cum}$ for recoverable injury.
- *TTS*: Fish-no SB and Fish w/SB not involved in hearing = NA *(cells C4 & C5)*
  - Exposure to mid-frequency sonar has not been known to induce TTS in fish species without swim bladders or in fish with swim bladders that are not involved in hearing (Halvorsen et al. 2012). In addition fish without swim bladders involved in hearing (i.e. close connections to the inner ear) do not sense pressure well and cannot hear at frequencies above 1 kHz.
- *TTS*: Fish w/ SB used in hearing = 220 dB $SEL_{cum}$ *(cell C6)*
  - Exposure to mid-frequency sonar has been known to induce TTS in some fish species with swim bladders and better hearing capabilities (Halvorsen et al. 2012). Criteria form Popper et al. (2014) was originally listed as > 210 dB $SPL_{rms}$. As previously stated, TTS criteria reported as cumulative sound exposure level ($SEL_{cum}$) accounts for the duration of the exposure as well. Therefore, the criteria originally presented in the technical report was converted to this metric using the duration of the signal reported from the experiments and was rounded down as a conservative measure (Halvorsen et al. 2012).

$$210 \text{ dB } SPL_{rms} + 10\log(15 \text{ sec}) = 221 \text{ dB } SEL_{cum}$$

- *Masking:* NA *(cells D4, D5, & D6)*
  - No data are available on masking by sonar but it is unlikely that sonar would mask important sounds for fish. The narrow bandwidth of most sonar would result in only a limited range of frequencies being masked (Popper et al. 2014). Furthermore most sonars are intermittent (i.e., low duty cycle) which further lowers the probability of any masking effects. Most mid-frequency sonars are above the hearing range of most fish species and almost all marine fish species (including salmonids).
- *Behavior:* Fish no SB and Fish w/ SB not involved in hearing = NA *(cells E4 & E5)*
  - Fish without swim bladders or without swim bladders involved in hearing would not be able to hear mid-frequency sonar; therefore, behavioral reactions would not occur.
- *Behavior:* Fish w/ SB involved in hearing = 200 dB $SPL_{rms}$ *(cell E6)*
  - No reactions were seen in herring exposed to 1-2 and 6-7 kHz sonar (Doksaeter et al. 2009, Doksæter et al. 2012). Therefore it is recommended that this criteria be 200 dB

$SPL_{rms}$ as a conservative measure. This criteria only applies to mid-frequency sonars up to 2.5 kHz since even fish with swim bladders with connections to the inner ear cannot hear above these frequencies with the exception of the taxa *Alosa* spp. (e.g., herring). While improbable (see Doksaeter et al. 2009, Doksæter et al. 2012), *Alosa* spp. could have behavioral reactions over the full bandwidth of mid-frequency sonar (1 – 10 kHz).

Navy Explosives

Note: Where values for explosives criteria were unknown, information from pile driving and seismic airgun studies were used as a proxy to propose criteria (Popper et al. 2014).

M*ortality and Mortal Injury:* 229 dB $SPL_{peak}$ *(cells A7, A8, & A9)*

- The proposed criteria is from Popper et al. (2014). Debusschere et al. (2014) was reviewed with regard to mortality from pile driving events; however, the levels tested did not reach those of the proposed criteria (210 – 211 dB $SPL_{peak}$, or 215-222 dB $SEL_{cum}$) and largely confirmed mortality results of previous lab experiments.

- *1% Mortality and No Injury:* Fish w/SB = Range equations *(B8 & B9)*
  - Maximum range to effect at any depth is provided in Young (1991) for 10% mortality (i.e. 90% survivability) based on O'Keeffe (1984). Yelverton et al. (1975) shows the relationship between impulse and percent mortality or no injury; Young's equation is modified to predict ranges to the 1% Mortality and No Injury zones based on the relationships between fish mass, impulse, and injury found in Yelverton et al. (1975).
- *TTS*: Fish-no SB = >>186 dB $SEL_{cum}$ *(cell C7)*
  - TTS data on fish exposed to seismic airgun signals Popper (2005) was used to derive the proposed explosive criteria. TTS data from explosions are not available. Direct (measured) TTS data from pile driving (or simulated pile driving noise) is also not available. Casper (2013) began observing inner ear hair cell loss indicative of threshold shift at levels between 213 and 216 dB $SEL_{cum,}$ in hybrid striped bass and Mozambique tilapia exposed so simulated pile driving sound. No fish exposed to 210 dB $SEL_{cum}$ exhibited any hair loss. However, taking the lowest level that produced TTS in a fish (Popper et al. 2005), and considering the fish without swimbladders should be less susceptible to TTS, the recommended TTS threshold is for fish with no SB is >> 186 dB $SEL_{cum}$.
- *TTS*: Fish w/SB not involved in hearing = >186 dB $SEL_{cum}$ *(cell C8)*
  - TTS data on fish exposed to seismic airgun signals Popper (2005) was used to derive the proposed criteria. TTS data from explosions are not available. Direct (measured) TTS data from pile driving (or simulated pile driving noise) is also not available. Casper (2013) began observing inner ear hair cell loss indicative of threshold shift at levels between 213 and 216 dB $SEL_{cum,}$ in hybrid striped bass and Mozambique tilapia exposed so simulated pile driving sound. No fish exposed to 210 dB $SEL_{cum}$ exhibited any hair loss. However, considering the lowest level that produced TTS in a fish (Popper et al. 2005), and that fish with a SB not involved in hearing should be less susceptible to TTS, the recommended TTS threshold is for fish with no SB is > 186 dB $SEL_{cum}$.
- *TTS*: Fish w/SB = 186 dB $SEL_{cum}$ *(cell C9)*
  - TTS data on fish exposed to seismic airgun signals from Popper (2005) was used to derive the proposed criteria. TTS data from explosions are not available. Direct (measured) TTS data from pile driving (or simulated pile driving noise) is also not available.
- *Masking:* NA *(cells D7, D8, & D9)*

  - Explosive sounds are brief in duration, lasting for only fractions of a second. Those generated by Navy training and testing are intermittent and infrequent in a given location. Therefore, auditory masking is unlikely due to explosive sounds from Navy training and testing.

- *Behavior: Fish w/ no SB =* (N)High, (I)Mod, (F)Low *(cell E7)*
  - Explosive sounds are brief in duration, lasting for only fractions of a second. Those generated by Navy training and testing are intermittent and infrequent in a given location. No data are available on behavioral reactions to explosives. The risk that explosives would result in a behavioral response decreases as the distance from the source increases. Popper et al. (2014) describes the probability of a behavioral response from a fish exposed to an explosive at near ranges (10's of meters) as high, intermediate ranges (100's of meters) as moderate, and at far ranges (>1000 m) as low. This would be highly dependent on the size of the explosive charge and the resulting magnitude of the sound. However, any behavioral reactions that would occur, such as startle responses, are not anticipated to cause life altering changes and would not likely effect the survivability of an individual.
- *Behavior: Fish w/ SB =* (N)High, (I)High, (F)Low *(cells E8 & E9)*
  - Explosive sounds are brief in duration, lasting for only fractions of a second. Those generated by Navy training and testing are intermittent and infrequent in a given location. No data are available on behavioral reactions to explosives. The risk that explosives would result in a behavioral response decreases as the distance from the source increases. Popper et al. (2014) describes the probability of a behavioral reaction by fish with swimbladders to explosives at near ranges (10's of meters) as high, intermediate ranges (100's of meters) as high, and at far ranges (>1000's of meters) as low. This would be highly dependent on the size of the explosive charge and the resulting magnitude of the sound. However, behavioral reactions anticipated to occur, such as startle responses, are not anticipated to cause life altering changes and would not likely effect the survivability of an individual.

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